# First Results from the CBI

B. S. Mason, T.J. Pearson, A.C.S. Readhead, M. Shepherd, J. Sievers, P. Udomprasert, J.K. Cartwright, S. Padin

*105-24 Caltech, Pasadena CA 91125*

**Abstract.**
The Cosmic Background Imager (CBI) is an instrument designed to measure intrinsic anisotropies in the cosmic microwave background (CMB) on angular scales from about 3 arc minutes to one degree (spherical harmonics of $\ell \sim 4250$ to $\ell \sim 400$). The CBI is a 13 element interferometer mounted on a 6 meter platform operating in ten 1-GHz frequency bands from 26 to 36 GHz. We present a review of the capabilities of the instrument and a discussion of observations which have been taken over the past year from the Atacama desert of Chile. We also present first results from the CBI which show a strong cutoff in the power spectrum between $\ell = 600$ and $\ell = 1200$ which is consistent with the photon-diffusive damping predicted by most models of structure formation in the early universe. We discuss future topics which the CBI will address.

## INTRODUCTION

Anisotropies in the Cosmic Microwave Background (CMB) contain a wealth of information about fundamental cosmological parameters [1], as well as providing a direct link to theories of high-energy physics [2]. The most straightforward models for anisotropies in the CMB (see, *e.g.*,[3]) feature two key physical scales: a length scale associated with acoustic oscillations of density fluctuations in the primordial plasma, and an exponential damping of these fluctuations caused by photon diffusion. Both of these physical scales depend upon the values of the cosmological parameters at and before the time of recombination, and the relation of these scales to observable angular scales on the sky is determined by the angular diameter distance between the present and $z = 1100$. If this basic picture is correct, the observable anisotropies are capable of strongly constraining the parameters of cosmology.

Inspired by the possibility of such accurate determinations of classical cosmological parameters, many experiments have sought and detected the most prominent large-scale CMB anisotropies due to the first Doppler peak (*e.g.*, [4, 5, 6, 7]). In these proceedings we report CBI measurements of intrinsic anisotropies on scales from $\ell =$ 600 to $\ell = 1200$. These measurements confirm the existence of a strong cutoff in the power spectrum and provide an independent constraint on the total energy density of the universe, $\Omega_{tot}$.

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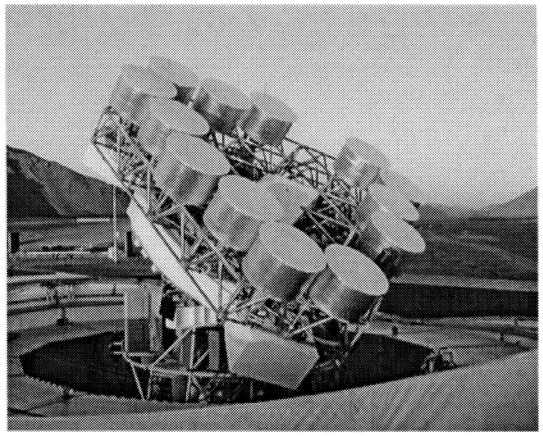

**FIGURE 1.** The CBI in the configuration in which the results reported in these proceedings were obtained.

## THE INSTRUMENT

The CBI is an interferometric array of 13 0.9-meter diameter antennas mounted on a 6-meter steerable platform, and operating in 10 1-GHz bands between 26 and 36 GHz ($\sim 1\,\mathrm{cm}$). Configurations available to the CBI yield synthesized beamwidths ranging from $4'$ to $15'$ (FWHM). Interferometry confers the significant advantage, relative to total power or beam-switched single-dish methods, of providing a *direct* measurement of $C_\ell$ on a scale determined by the baseline length. The range of baselines available to the CBI correspond to $400 < \ell < 4250$. By changing the array configuration of the CBI, the instrument's sensitivity can be optimized for varying ranges of $\ell$. The primary beam width $44'$ (FWHM at 30 GHz) implies a resolution $\delta\ell \sim 420$ (FWHM); this can be significantly improved by mosaicked observations. One configuration of the CBI is shown in Figure 1.

The key design challenges in the project were eliminating cross-talk in a compact array and developing a wide-band correlator. Receiver noise scattering between adjacent antennas (cross-talk) causes false signals at the correlator output and this could limit the sensitivity of the instrument. We developed a shielded Cassegrain antenna with low scattering to reduce the cross-talk [8]. The antennas have machined, cast aluminum primaries which sit at the bottom of deep cylindrical shields. The upper rims of the shields are rolled with a radius of a few wavelengths to reduce scattering from the shield itself. The secondaries are made of carbon fiber epoxy, to minimize weight, and supported on transparent polystyrene feed legs. Cross-talk between the antennas is $< -110$ dB in any CBI band.

The antennas are mounted on a rigid tracking platform supported by an altazimuth mount that is fully steerable to elevations $> 42°$. The antenna platform can be rotated about the optical axis. In normal observations, the platform tracks the parallactic angle so that observations are made at fixed $(u,v)$ points: i.e., the baseline orientations are fixed relative to the sky. Additional discrete steps in the orientation of the platform are used to change the baseline orientations and thus sample more $(u,v)$ points.

The correlator [9] is an analog filter bank correlator with ten 1-GHz bands. A fast phase-switching scheme, in which the receiver local oscillators are inverted in Walsh function cycles, is used to reject cross-talk and low-frequency pickup in the signal processing system. The system is calibrated by nightly observations of celestial sources; CMB data are referenced onto this scale by comparison with an internal source of correlated noise which is injected before the first stage of each receiver. Variations in the calibration of the CBI are at the 1% and 1 deg level. Further discussion of the instrument can be found in [10].

Construction of the CBI was begun in August 1995 in Pasadena, CA on the Caltech campus, and completed in January 1999. After a period of test observations in Pasadena, the telescope was disassembled and shipped in August 1999 to its site high in the Chilean Andes. This site, at an altitude of 5000 meters, was chosen in order that our sensitivity not be limited by atmospheric water vapor emissions. First light in Chile was achieved November 1, 1999, and routine observations have been taken from January 2000 to the present.

## OBSERVING STRATEGY AND FIRST RESULTS

Our observing strategy is dictated by the fact that, on the shortest CBI baselines, the ground produces significant correlated signals. To remove these, pairs of (LEAD/TRAIL) fields are observed over identical ranges in azimuth and elevation. The difference between these data cancels ground-based signals. This differencing also controls other possible systematics due, *e.g.*, to correlator offsets or antenna cross-talk. From January through April 2000, observations of two pairs of such fields (C0844−0310 and C1442−0350) were taken in a test configuration providing a maximally uniform distribution of baseline lengths and easy access to all receivers. In all $\sim 160$ hours of integration were obtained. The data are calibrated with reference to Jupiter at 32 GHz, using $T_J = 152 \pm 5\,\mathrm{K}$ [11]. Since Jupiter does not have a simply thermal spectrum, this calibration is bootstrapped to other frequencies using TauA, which has a known power-law spectrum between 26 and 36 GHz.

The difference image of the C0844 field is shown in Figure 2. The observed signal is confined to the telescope main beam, indicating that it is of celestial origin. We have searched for contaminating signals by dividing the data by epoch and by zenith angle and differencing the resulting datasets, yielding a doubly-differenced dataset which in the absence of contaminating signals should be consistent with thermal noise. The zenith angle tests showed no measureable excess signal; from this we conclude that our LEAD/TRAIL differencing leaves no significant residual ground signal in the data. There is a slight noise excess in the data when divided by epoch which amounts to a $< 1.5\%$ contamination in $C_\ell$. This could be due to slight changes in the instrument calibration over long periods of time, but at present this excess is not understood in detail.

In order to remove discrete radio sources, the dominant foreground to CMB measurements at our frequency and resolution, dedicated observations of sources selected from

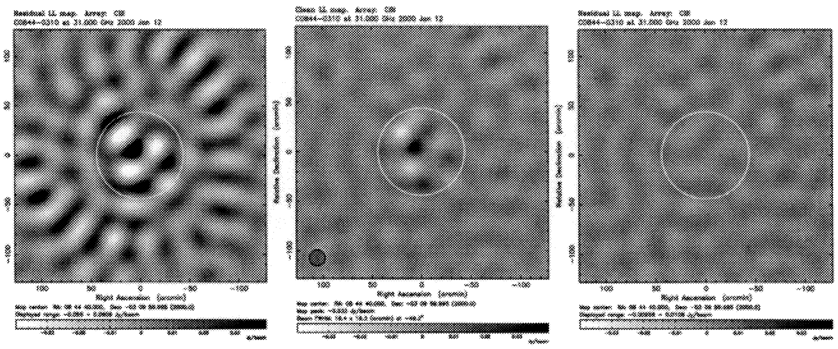

**FIGURE 2.** Differenced image of the $08^h$ field observed on the 100 and 104 cm CBI baselines (left), an image with the point spread function deconvolved (center), and the residuals after subtraction of the deconvolved signal (right). The large circles in the map centers indicate the 5% power level of the telescope primary beam (2 FWHM $\sim 88'$); the small circle in the lower left of the center map indicates the synthesized beamwidth of $\sim 16'$ FWHM

the NVSS[12] are conducted at 30 GHz with the OVRO 40-meter telescope. Sources detected by the 40-meter are subtracted directly from the CBI data. The bright source subtraction affects our results on these scales by less than 2%, and the longer baseline data show no evidence for bright missed sources.

Our data give a robust detection of CMB anisotropy on scales from $\ell = 300$ to $\ell = 1500$. A maximum-Likelihood analysis of the visibility data gives flat bandpowers ($\delta T_{band} \equiv [\ell(\ell+1)\overline{C_\ell}/(2\pi)]^{1/2} \times T_{cmb}$) of $\delta T_{band} = 58.7^{+7.7}_{-6.3}\,\mu$K for $\ell = 603^{+180}_{-166}$ and $\delta T_{band} = 29.7^{+4.8}_{-4.2}\,\mu$K for $\ell = 1190^{+261}_{-224}$. These results are shown in Figure 3.

Currently only weak constraints on the spectral index are available and only in the lower $\ell$ bin. In this range we find a temperature spectral index $\beta = 0.0 \pm 0.4\,(1\sigma)$, where $\beta = 0$ corresponds the a thermal blackbody spectrum. For the realistic case that the foreground powers $[\ell(\ell+1)C_\ell]$ are falling as $\ell^{-0.2}$, then at the $2\sigma$ limit a free-free foreground would contribute 15% to the observed power in the first bin, and a synchrotron foreground would contribute 11%. Our data are also consistent with no foreground contribution to the observed power level. Furthermore, the C0844$-$0310 and C1442$-$0350 fields show different levels of emission in our foreground templates (IRAS and synchrotron maps), but the power levels observed by the CBI at 32 GHz in these two fields are consistent.

A cosmological maximum-Likelihood analysis of these data yields $\Omega_{tot} \leq 0.4$ or $\Omega_{tot} \geq 0.7$ (90% confidence).

More discussion of this analysis can be found in [13].

## FURTHER SCIENCE WITH THE CBI

Observations of two $5^\circ \times 3^\circ$ mosaic fields and one $5^\circ \times 6^\circ$ field have been completed and the analysis of these data is in progress. When complete, these results will improve our

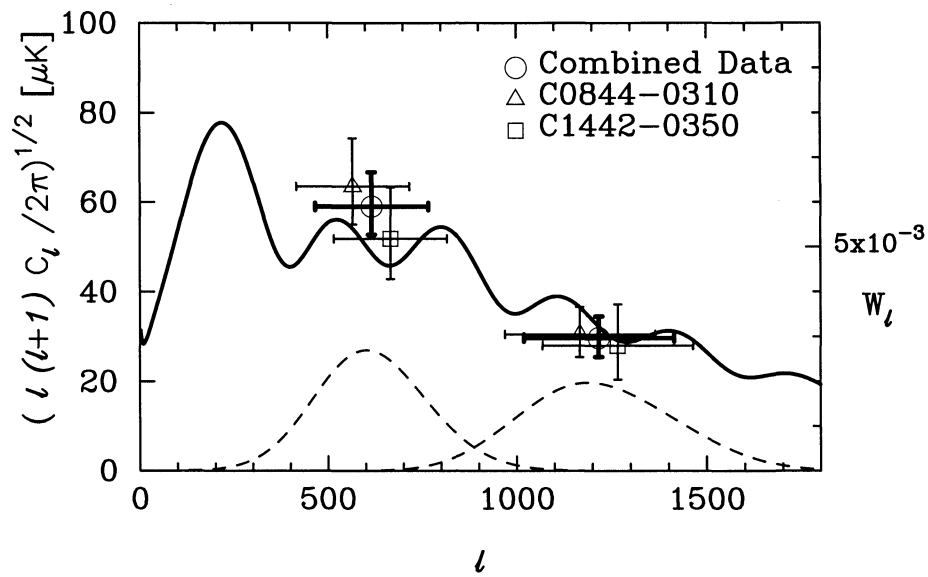


**FIGURE 3.** The CMBR anisotropy spectrum determined from CBI observations. The triangles and squares show results on the $08^h$ and $14^h$ differenced fields; the circles show the results of a joint maximum likelihood analysis of both differenced fields. The individual $08^h$ and $14^h$ field results are offset in $l$ for clarity. The window functions for each bin are shown as dashed lines. The solid curve represents a flat universe with $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_b h^2 = 0.019$, and $\Omega_{cdm} = 0.2$.

resolution in $\ell$ by a factor of $3-4$. We have also acquired data to improve the spectral index constraints on the signal out to $\ell \sim 1200$.

The CBI has one cross-polarized antenna. This will enable stringent limits to be placed on the CMB polarization in the vicinity of the second Doppler peak in the polarization power spectrum. Polarization data were acquired on the CBI fields from January through December 2000 and the analysis of these data is in progress.

The range of angular scales available to the CBI is also well-suited to measuring the Sunyaev-Zeldovich Effect (SZE) in nearby galaxy clusters. A campaign to determine $H_0$ from observations of the SZE in a sample of 20 $z < 0.1$ clusters is underway with the CBI. This campaign has the feature of selecting targets from an orientation-unbiased sample [14]. The large sample size is important for reducing the effects of intrinsic CMB anisotropy, and for understanding possible X-ray modelling systematics associated with clusters at a range of dynamical states. Previous results from a similar program with the OVRO 5-meter telescope have been presented in [15].

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